DISTINGUISHING SOLAR FLARE TYPES BY DIFFERENCES IN RECONNECTION REGIONS

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ABSTRACT

Observations show that magnetic reconnection and its slow shocks occur in solar flares. The basic magnetic structures are similar for long duration event (LDE) flares and faster compact impulsive (CI) flares, but the former require less non-thermal electrons than the latter. Slow shocks can produce the required non-thermal electron spectrum for CI flares by Fermi acceleration if electrons are injected with large enough energies to resonate with scattering waves. The dissipation region may provide the injection electrons, so the overall number of non-thermal electrons reaching the footpoints would depend on the size of the dissipation region and its distance from the chromosphere. In this picture, the LDE flares have converging inflows toward a dissipation region that spans a smaller overall length fraction than for CI flares. Bright loop-top X-ray spots in some CI flares can be attributed to particle trapping at fast shocks in the downstream flow, the presence of which is determined by the angle of the inflow field and velocity to the slow shocks.

Subject Headings : Magnetic Fields: MHD; Acceleration of Particles; Sun: magnetic fields, flares, corona.

1. Introduction

Solar flares are rapid bursts of radiation from the solar atmosphere. They have long been believed to result from the conversion of magnetic energy (e.g. Pneuman 1981) by magnetic reconnection (e.g. Biskamp 1994), a process in which oppositely magnetized flows merge across a thin dissipation region (DR). Recent flare X-ray observations from the Yohkoh satellite (e.g. Tsuneta et al. 1992; Masuda et al. 1994) have confirmed that reconnection is fundamental to the observed energy release.

Flares are divided into two classes (Pallavicini 1991), the long duration event (LDE) two-ribbon flares and the compact impulsive (CI) flares. The former, with typical durations of hours, and luminosities $\sim 10^{28}$erg/sec, have been modeled as the merging of magnetic field lines at the top of an inverse-Y type field line configuration (Fig. 1). Downward ejected plasma heats photospheric footpoints, inducing a flux loop filling upward flow that generates soft X-rays (e.g. Sturrock 1966; Tsuneta 1996ab). LDEs are of order $10^4 - 10^5$ km in height, have generally smooth time profiles and not much non-thermal electron emission (e.g. Tsuneta 1996a).

CI flares are $\lesssim 1/10$ the size of LDE flares, lasting of order minutes, and with similar luminosities (e.g. Masuda et al. 1994). They show strong impulsive phases with bursts of non-thermal emission and variability times $\sim$ O(0.1) sec. One of the intriguing implications of the CI Masuda flare (Masuda et al. 1994) observations is that the fundamental inverse-Y configuration and the downward plasma flow are likely common to the CI as well as to the LDE flares, in contrast to what was previously thought. The CI Masuda flare is also

interesting for its hard X-ray source at the top of its soft X-ray loop in addition to the usual hard X-ray footpoints.

Yohkoh observations indicate the presence of slow shocks in at least some flares (Tsuneta 1996ab). This provides support for Petschek (Petschek 1964) or Sonnerup (Sonnerup 1970) type rapid reconnection models, i.e. those in which slow shocks extend from the corners of the thin DR, dividing the inflow and outflow. The length of the slow shocks vs. the length of the DR likely depends on boundary and inflow conditions (Priest & Forbes 1986; Forbes & Priest 1987). Priest & Forbes (1986) have shown that a variety of solutions can be obtained by changing the angle of inflow velocity to the reconnection region.

Though the basic reconnection configuration and the plasma filling of a soft X-ray loop are common to LDE and CI flares, the relative sizes of the DR and its shocks and their distance from the chromosphere are likely important in determining differences in the number of non-thermal electrons reaching the footpoints. Section 2 addresses how reconnection slow shocks may be a source of particle acceleration. Section 3 describes how the DR is important in injecting electrons into the shocks and determining the extent of non-thermal acceleration. In section 4, the condition for a downstream fast shock is derived in terms of the inflow parameters. In section 5, a more specific discussion distinguishing flares is given, and section 6 is the conclusion.

2. Acceleration at Slow Shocks

Flare reconnection occurs at the very top of the configuration of Fig. 1 as regions

of oppositely magnetized plasma flow in from the sides and intersect at the thin DR. The magnetic annihilation produces a topology change with an X-point at the interface. The shocks occur at the boundaries between inflow and outflow. Unlike fast shocks, slow shocks have a weaker magnetic field downstream than upstream. Fermi acceleration is still possible at these shocks (Blackman & Field 1994; Blackman 1996). To see this, note that the MHD shock jump conditions for mass, momentum, energy, and electromagnetic fields are (e.g. Melrose 1986)

$$\rho_1 v_{1n} = \rho_2 v_{2n}, \tag{1}$$

$$\rho_1 v_{1n}^2 + P_1 + B_{1t}^2/8\pi = \rho_2 v_{2n}^2 + P_2 + B_{2t}^2/8\pi \ ; \ \rho_1 v_{1n}\mathbf{v_{1t}} - B_{1n}\mathbf{B_{1t}}/4\pi = \rho_2 v_{2n}\mathbf{v_{2t}} - B_{2n}\mathbf{B_{2t}}/4\pi, \tag{2}$$

$$(1/2)\rho_1 v_1^2 v_{1n} + \Gamma(\Gamma-1)^{-1}P_1 v_{1n} + (B_1^2/4\pi)v_{1n} - \mathbf{v_1}\cdot\mathbf{B_1}B_{1n}/4\pi = (1/2)\rho_2 v_2^2 v_{2n}$$

$$+\Gamma(\Gamma-1)^{-1}P_2 v_{2n} + (B_2^2/4\pi)v_{2n} - \mathbf{v_2}\cdot\mathbf{B_2}B_{2n}/4\pi, \tag{3}$$

$$B_{1n} = B_{2n} \ ; \ (\mathbf{v_1}\mathrm{x}\mathbf{B_1}) = (\mathbf{v_2}\mathrm{x}\mathbf{B_2}). \tag{4}$$

where B is the magnetic field, v is the velocity, P is the pressure, ρ is the density and Γ is the adiabatic index. The subscript 1(2) refers to the up(down)stream region, and the subscript $n(t)$ refers to the normal (tangential) components.

The shock is $\perp$ to the $\hat{\mathbf{n}}, \hat{\mathbf{y}}$ plane as shown in Fig. 2. We assume the switch-off condition, $B_{2y} = 0$, and also that $\mathbf{v}_1/|v_1| \cdot \hat{\mathbf{y}} << 1$. Define $\tilde{C} \equiv cos\theta$, $\tilde{S} \equiv sin\theta$ and $\tilde{T} \equiv tan\theta$ where θ is the angle between the downstream flow and the shock normal. Define $C_1 \equiv cos\phi_1$, $S_1 \equiv sin\phi_1$ and $T_1 \equiv tan\phi_1$ where ϕ_1 is the angle between the upstream field

and the shock normal. The configuration of Fig. 2 is then described by

$$v_{1n} = -v_1,\ B_{1n} = -B_1 C_1,\ B_{1y} = -B_1 S_1, v_{2n} = -v_2 \tilde{C},\ v_{2y} = v_2 \tilde{S},\ B_{2n} = -B_2,\ v_{1y} = B_{2y} = 0. \tag{5}$$

For $\Gamma = 5/3$ and $\beta_1 \equiv a_{1s}^2/v_{1A}^2 << 1$, where a_{1s} and v_{1A} are the inflow sound and Alfvén speed, plugging (5) into (1-4) gives

$$T_1^2 = 2(r_s - 1)(r_s - 4)/(5r_s - 2r_s^2), \tag{6}$$

$$\beta_2 = (5/3)[(r_s - 1)/r_s + T_1^2/2] \tag{7}$$

$$M_{2A}^2 \equiv v_2^2/v_{2A}^2 = (1 + r_s^2 T_1^2)/r_s, \tag{8}$$

where M_{2A} is the outflow Mach number, v_{2A} is the outflow Alfvén speed, $\beta_2 \equiv a_{2s}^2/v_{2A}^2$, a_{2s} is the outflow sound speed and $r_s \equiv \rho_2/\rho_1$. Since $T_1^2 > 0$, (8) shows that $2.5 \leq r_s \leq 4$ for a low β_1 switch-off shock (Kantrowitz & Petschek 1966; Blackman & Field 1995), with the lower limit being a perpendicular ($\perp$) shock and the upper limit a parallel ($||$) shock.

The equation for diffusion and convection of particles across a shock is given by (Jones & Ellison 1991)

$$\partial_n[v_n f - \kappa_n \partial_n f] - (1/3)(\partial_n v_n)\partial_p[pf] = 0, \tag{9}$$

where f is the particle distribution function, v_n is the normal flow velocity across the shock, p is the particle momentum, $\kappa_n \sim p\lambda/3m$ is the normal diffusion coefficient, λ is the mean-free path between particle-wave scatterings, and m is the particle mass. Fermi acceleration operates as particles diffuse between scattering centers (presumably MHD Alfvén turbulence) on each side of the shock. Particles always see the centers converging, as

the normal velocity is larger upstream. The solution of (9) across the shock with thickness $<$ mean-free path (Jones & Ellison 1991) shows that the outflow particle spectrum for a steeper inflow spectrum takes the power law form $f \propto p^{-\alpha}$, with index $\alpha = (r_s{+}2)/(r_s{-}1)$, where p is related to the energy E by $p = E^{1/2}(E + 2mc^2)^{1/2}/mc$. Thus for weakly or non-relativistic particles, $f(E) \propto E^{-2\alpha}$. For $2.5 < r_s < 4$, $4 \leq 2\alpha \leq 6$ for the slow shocks, which is quite consistent with the required electron spectra derived by inverting the observed photon spectrum from thick target models of X-ray footpoints of solar flares (Aschwanden & Schwartz 1996). Slow shocks may therefore supply non-thermal electrons.

Though $4 < 2\alpha < 6$ results from an analytical treatment, shock acceleration is a very non-linear process. Fermi acceleration can be even more efficient in the non-linear regime, transferring $\geq 1/2$ of the inflow energy to particles (Jones & Ellison 1991). Similar beam instabilities to those which signature Fermi acceleration in fast shocks have also been seen in slow shock simulations (Omidi & Winske 1994). Support for slow shock acceleration is present in the geomagnetic tail where turbulence, required for Fermi acceleration, is seen on both sides of the shock fronts (Coroniti, et al. 1994) and non-thermal tails in the electron spectra are seen (Feldman et al. 1990).

3. Electron Injection and Solar Flare Reconnection

For CI flares, unlike LDE flares, $>$ 20keV non-thermal electrons may contribute to of order the total luminosity (Lin & Hudson, 1971). Electrons can only be shock accelerated when they are injected above a critical energy a factor of the mass ratio (m_p/m_e) higher than that required by protons. Fermi acceleration requires downstream particles to scatter

upstream and gain energy from turbulent scattering centers that boost only the momentum parallel to the magnetic field. Pitch-angle randomizing must occur in order for multiple energy gains to be imparted (Eilek & Hughes 1991). This randomization is provided by resonant Alfvén waves which exist with frequencies only below the ion gyro-frequency.

For Alfvén turbulence (Eilek & Hughes 1991) in the limit that the Alfvén speed exceeds $m_e c/m_p$, the lower bound on the Lorentz factor for electrons to resonate with Alfvén waves is $\gamma_e \gtrsim 1 + (m_p/m_e)(v_{2A}/c)^2$ for $v_{2A}^2 < (m_e/m_p)^2 c^2$ while for $v_{2A}^2 > (m_e/m_p)^2 c^2$, $\gamma_e \gtrsim (m_p/m_e)(v_{2A}/c)$. For reconnection shocks, stochastic acceleration (e.g. Larosa 1996) in the DR may provide injection electrons with self-generated Alfvén waves. To see that this is kinematically feasible, note that upon absorbing the annihilated field energy in the DR, the average γ_e there could be $\sim 1 + (v_{1A}^2/c^2)(m_p/m_e)$. Since $v_{1A} \geq v_{2A}$ for a slow shock, the DR can in principle always inject. Since all field lines in a reconnection region which pass through the shock also pass through the DR, the fraction of electrons that could be injected and accelerated is at least the fraction that passes through the DR.

4. Formation of and Acceleration at Fast Downstream Shocks

When $\mathbf{B}_2 \cdot \mathbf{v}_2/|B_2 v_2| << 1$, v_2 will be supermagnetosonic (Melrose 1986) when $v_2^2 = v_{2n}^2 + v_{2y}^2 > a_{2s}^2 + v_{2A}^2$. Using (1-5) this reduces (Blackman & Field 1994) to $6r_s^2 - 13r_s - 20 < 0$, which is satisfied for $r_s \lesssim 3.2$ or $T_1 > 1.25$ from (6). A supermagnetosonic outflow becomes the condition for a fast shock when the field is line-tied at the outflow boundary. The jump conditions (1-4) across such a quasi-$\perp$ fast shock for $\Gamma = 5/3$ give

$$M_{2A}^2 = 3r_f\beta_2/(4 - r_f) + (3/2)r_f(r_f - 1)/(4 - r_f), \tag{10}$$

where r_f is the compression ratio across the fast shock. Using (6-8) and (10), it can be shown that $1 \lesssim r_f \lesssim 2$ when $2.5 \lesssim r_s \lesssim 3.2$. The inverse dependence is expected because a decrease in r_s corresponds to an increase in tension force along the shock plane, and thus a larger M_{2A}, accounting for the larger r_f.

Thus, the stronger the inflow field tangential to the slow shock, the more likely the presence of an outflow fast shock. But the condition for a fast shock was determined in the frame for which the inflow is $\perp$ to the shock. If the lab frame inflow has a tangential component parallel to that of the outflow, the minimum T_1 for a shock would decrease, while a tangential component opposite to the outflow would increase the minimum T_1. The absence or presence of a downstream fast shock can be used as a diagnostic to determine whether the flow is converging or diverging on each side of the DR. This determines the mode of reconnection (Forbes & Priest 1986).

5. Application to Flares

The bright X-ray source above the CI Masuda flare loop top may be associated with favorable inflow conditions for an outflow fast shock. Time of flight (TOF) analyses (Aschwanden et al. 1996) require loop-top electron trapping either by collisional trapping, or from an enhanced site of Alfvén waves. The presence of a fast shock as a site of turbulence may provide the latter. Since $r_f < r_s$ as computed above, trapping, rather than acceleration, could be the fast shock's primary purpose. The TOF analysis of the Masuda flare also suggests that the actual acceleration region is located above the loop-top X-ray source (Aschwanden et al. 1996) which is consistent with the present picture. Also consistent is

the fact that the loop top source and the footpoint sources are observed to mimic each others' temporal behavior. If slow shocks are responsible for acceleration, some of the fast particles will escape toward the loop top, and others toward the footpoints, with the source of acceleration being the same for both.

In the approach of Larosa et al. (1996), stochastic turbulence in the outflow of a reconnection region is suggested as a possible source of CI flare electron acceleration. It is likely that stochastic and slow shock acceleration have a symbiotic relationship. Stochastic acceleration near the DR could provide the injection electrons which are subsequently accelerated along the shock. Away from the DR in the outflow, the field is very small, and the stochastic acceleration would not be effective there. It would be difficult to explain the differences between loop top X-ray source CI flares and those which just have brightened footpoints without at least invoking a downstream fast shock. But the canonical compression ratio of the fast shock, as estimated above, may not be high enough to account for all of the acceleration. Since it is known that in LDE flares the slow shocks are involved in heating (Tsuneta 1996a), their role for electron acceleration in CI flares may also be important as described herein.

Stochastic acceleration provides the upper limit on the variability time scale, t_{sh}, resulting from injection+shock Fermi acceleration, since all turbulent scattering collisions in the latter mechanism 'head-on' making it more efficient. This gives $t_{sh} \sim \kappa_n/v_1^2 \lesssim t_{sto} \sim w/v_{1A}$ (Larosa et al. 1996) where w is the width of the reconnection outflow. For the Masuda flare, $v_{1A} \sim 5 \times 10^8$cm/sec and $w \lesssim 10^8$cm so that $t_{sh} \lesssim 0.25$sec, consistent

with time scales of CI flare spikes (e.g. Aschwanden et al. 1995). Later we find the thermalization time of electrons is larger than t_{sto}, so that Fermi acceleration should dominate all Coulomb collisions at the acceleration sites.

For non-thermal electrons to reach the footpoints, the electrons must not collisionally thermalize before arriving. The time scale for a density of electrons, n, with average energy ϵ to thermalize is given by (Stepney 1983) $t_{th} \sim 8.5(\epsilon/25\mathrm{keV})^{3/2}(n/10^{10}\mathrm{cm}^{-3})^{-1}(\ln\Lambda/20)^{-1}\mathrm{sec}$, where $\ln\Lambda$ is the Coulomb logarithm. Avoiding thermalization requires that the distance from the shocks to the footpoints at least satisfies $D < [\xi(2\epsilon/m_e)^{1/2} + (1-\xi)v_2]t_{th}$, where ξ is the fraction of accelerated particles that can move directly along a field line to a footpoint. (Many of the accelerated particles will come from the outflow region where the field is horizontal, and because of the their small gyro-radii even in the outflow, they can only convect to footpoints at the outflow speed.) The above condition on D might not be met for an LDE flare with small ξ since the outflow velocity (e.g. Tsuneta 1996a) is $v_2 \sim v_{1A}/r_s^{1/2} \sim 10^8$cm/sec. Thus $v_2 t_{th} \sim 1.4 \times 10^9$cm, which is too small by an order of magnitude or so. However, for the typically smaller CI flares, the reconnection outflow is $\gtrsim 5$ times faster (e.g. Masuda et al. 1994) so $v_2 t_{th} \sim 7 \times 10^9$cm, and this would be large enough to allow canonical non-thermal electrons to convect to typical CI flare footpoints (Aschwanden et al. 1996).

The number of electrons/sec, N, reaching the footpoint sites for CI flares would be comprised of those injected first by the DR. This is given by $N \sim t_{sh}^{-1} n V_{dif}$, where the DR volume is $V_{dif} \sim R^2 h \sim R^3(v_1/r_s v_2)$ with R and h the DR length and thickness

(Fig. 2), and the last similarity follows from mass flux conservation through the DR. Now $v_1 \sim 8\pi L_{nt}/B_1^2 R^2$ where L_{nt} is the non-thermal luminosity and $v_2 \sim v_{1A}/r_s^{1/2}$. Thus

$N \sim 10^{35}(t_{sh}/0.25\mathrm{sec})^{-1}(n/10^{10}\mathrm{cm}^{-3})^{3/2}(B_1/200\mathrm{G})^{-3}(L_{nt}/10^{28}\mathrm{erg/sec})(r_s/3)^{-1/2}(R/4\times 10^8\mathrm{cm})\mathrm{sec}^{-1}$. The scalings are reasonable for the CI Masuda flare. Electron injection from the DR followed by further processing in the shocks is therefore feasible. Note that R need only be $\sim 1/15$ of the overall height to the DR in the Masuda flare.

For LDEs the DR length fraction would be even less. The DR of the Feb 21 LDE flare (Tsuneta 1996a) occupies a tiny fraction of the overall region, qualitatively consistent with the present picture. The absence of a fast shock in this LDE suggests that the inflows to the DR are converging flows. This is because $T_1 \sim 5$ (Tsuneta 1996a) which is above the threshold for a downstream fast shock, so the inflows must be converging to make the effective condition for an outflow shock more stringent. This is also consistent with having a small DR in the unified reconnection models of Priest & Forbes (1986).

6. Conclusions

Different combinations of slow and fast shocks and stochastic acceleration may lead to different flare types from similar basic inverse-Y structures. Non-thermal acceleration from slow shocks is likely most effective when the thin DR is long enough to provide injection electrons which can subsequently be shock accelerated. The canonical spectrum from Fermi acceleration at slow reconnection shocks reasonably matches the required CI flare electron spectrum (Aschwanden & Schwartz 1996). If the DR were very large, then stochastic Fermi acceleration could dominate. To summarize, the absence of significant

non-thermal electrons reaching the footpoints for LDE flares would result from both a small DR length and its larger distance from the footpoints compared to CI flares. CI flares with loop top X-ray sources would have a very strong inflow magnetic field component along the slow shocks, enabling an outflow fast shock to form.

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Achterberg, A., 1987, in *Astrophysical Jets and Their Engines*, W. Kundt ed., NATO series C, vol 208, (Dodrecht: Reidel).

Aschwanden, M.J., Schwartz, R.A., & Alt, D.A., 1995, ApJ, **447**, 923.

Aschwanden, M.J. et al., 1996, ApJ, **464**, 985.

Aschwanden, M.J., & Schwartz, R.A., 1996 **464**, 974.

Biskamp,D., 1994, Phys. Rep., **237**, 179.

Blackman, E.G. & Field, G.B., 1994, Phys Rev. Lett, **73**, 3097.

Blackman, E.G., 1996, ApJ, **56**, L87.

Coroniti,F.V. et al., (1994), J. Geophys. Res., **99**, 11251.

Eilek,J.A., & Hughes, P.A., 1991, in *Beams and Jets in Astrophysics*, ed. P.A. Hughes, (New York: Cambridge Univ. Press).

Feldman,W.C. et al., 1990, J. Geophys. Res., **90**, 233.

Jones,F.C., & Ellison,D.C., 1991, Space Sci. Rev., **58**, 259.

Kantrowitz, A., & Petschek,H.E., 1966 in *Plasma Physics in Theory and Application* edited by W. B. Kunkel, (New York: McGraw-Hill).

Larosa, T.N. et al., 1996, ApJ, **467**, 454.

Lin R.P. & Hudson, H.S., 1971, Sol. Phys., **17**, 412.

Masuda, S. et al., 1994, Nature, **371**, 495.

Melrose, D.B., 1986, *Instabilities in Space and Laboratory Plasmas* (Cambridge: Cambridge Univ. Press).

Pallavicini, R., Phil. Trans. R. Soc., 1991, A**336**, 389.

Pneuman, G.W., 1981, in *Solar Flare Magnetohydrodynamics*, ed. E.R. Priest, (New York: Gordon & Breach).

Omidi, N. & Winske, D., 1994, J. Geophys. Res., **97**, 14801.

Petschek, H.E., 1964, AAS-NASA Symp on Phys. of Solar Flares, NASA SP-50, 425.

Priest, E.R. & Forbes, T.G., 1986, J. Geophys.Res **91**, 5579.

Forbes, T.G. & Priest, E.R., 1987, Rev. Geophys. **25**, 1583.

Parker, E.N., *Cosmical Magnetic Fields*, 1979, (New York: Oxford University Press).

Sonnerup, B.U.Ö, 1970, J. Plasma Phys., **4** 161.

Sturrock, P.A., 1966, Nature **211**, 695.

Tsuneta S. et al., 1992, PASJ, **44**, L63.

Tsuneta, S., 1996a, ApJ, **456**, 840.

Tsuneta, S., 1996b, in *Observations of Magnetic Reconnection in the Solar Atmosphere*, ed. B. Bentley and J. Mariska, PASP conf., in press.

Figure Captions

Figure 1

Canonical solar flare structure. The hard X-ray sites shown are characteristic of smaller CI flares rather than LDE flares but the overall flare structure is the same. The X-point lies within the dissipation region at the top between the merging inflows. Only the downward outflow from the dissipation region is shown but there is also a vertical outflow.

Figure 2

Schematic of the reconnection region flows and fields in the switch off shock case analyzed in the text. The dotted line is a possible outflow fast shock.